DYNAMICS OF SURFACE BARLEY RESIDUES DURING FALLOW AS AFFECTED BY TILLAGE AND DECOMPOSITION IN SEMIARID ARAGON (NE SPAIN)

M.V. López*, J.L. Arrúe, J. Álvaro-Fuentes, D. Moret

Departamento de Edafología, Estación Experimental de Aula Dei, Consejo Superior de Investigaciones Científicas (CSIC), POB 202, 50080-Zaragoza (Spain)

* Corresponding author. Tel.: 34-976-71 61 46; fax: 34-976-71 61 45
E-mail address: vlopez@eead.csic.es.

Abstract

Most of the benefits from conservation tillage are attained by maintaining crop residues on the soil surface. However, the effectiveness of crop residues depends on their persistence in time and maintenance of sufficient residue cover can become difficult, especially when a long-fallow period is involved. In this study, we evaluate the effects of conventional tillage (CT) and two conservation tillage systems (reduced tillage, RT, and no-tillage, NT), under both continuous cropping (CC) and cereal-fallow rotation (CF), on the dynamics of surface barley residues during four fallow periods in a dryland field of semiarid Aragon. The CC system involves a summer fallow period of 5-6 months and the CF rotation a long-fallow of 17-18 months. Results indicate that the lack of residue-disturbing operations in NT makes this practice the best strategy for fallow management. With this tillage system, the soil surface still conserved a residue cover of 10-15% after long-fallowing and percentages of standing residues ranging from 20% to 40% of the total mass after the first 11-12 months. In both CT and RT, primary tillage operations had the major influence on residue incorporation, with percentages of cover reduction of 90-100% after mouldboard ploughing (CT) and 50-70% after chiselling (RT). Two decomposition models were tested, the Douglas-Rickman and the Steiner models. Our data indicate that the Steiner model described more accurately the decline of surface residue mass over the long-fallow period in the NT plots. Measured and predicted data indicate that, under NT, 80-90% of the initial residue mass is lost at the end of fallow and that 60-75% of this loss occurs during the first 9-10 months. Finally, the mass-to-cover relationship established in this study for barley residues could be used to predict soil cover from flat residue mass through the fallow period by using a single A_m coefficient (0.00208 ha kg^{-1}).

***Keywords**:* Barley residues; Conservation tillage; Fallowing; Residue cover; Standing residues; Decomposition models.

Introduction

Soil and water conservation is an issue of primary concern in agricultural lands of Central Aragon (NE Spain). In this region, one of the driest in the Iberian peninsula and one of the northernmost semiarid areas of Europe, crop production is limited by low and extremely variable precipitation. In addition, strong and dry WNW winds (*Cierzo*) with high frequency of erosive events are common all year around. Soils are poorly structured, mostly alkaline, with low organic matter content and a dominant sandy loam to loam textural class. Besides these soil and climate characteristics, inadequate agricultural practices make this region prone to land degradation by wind erosion (López et al., 2000, 2001). The main cropping system is the traditional cereal-fallow rotation (one crop in two years). This rotation extends over about 430,000 ha with an annual precipitation less than 400 mm and implies a long-fallow period of 16-18 months. During fallowing, the risk of wind erosion increases due to insufficient crop residue cover and highly pulverised soils by repeated tillage.

Conservation tillage has been proposed as a fallow management alternative to preserve soil and water resources in semiarid Aragon. In fact, previous results have demonstrated that reduced tillage is an effective practice to reduce soil losses by wind erosion in the months following tillage during fallow (López et al., 1998, 2001; Gomes et al., 2003). Most of the benefits from conservation tillage are attained by maintaining crop residues on the soil surface (Kumar and Goh, 2000; Gajri et al., 2002). However, the effectiveness of crop residues depends on their persistence in time and the amount of surface residues can be reduced considerably by tillage and decomposition (Lindwall et al., 1994; Guérif et al., 2001). Therefore, information about tillage effects on residue incorporation into the soil and rates of residue decomposition is essential in order to evaluate effective management strategies for conservation purposes in semiarid Aragon.

Most studies on crop residue dynamics over time have performed decomposition experiments under controlled laboratory conditions or under field conditions using the mesh bag technique. Even though these methodologies imply less labor requirements and lower sources of error than the grab sampling in the field, they have been questioned in relation to the difficulty of extrapolating data from controlled environments to natural field conditions (Kumar and Goh, 2000). Steiner et al. (1999) and Ruffo and Bolero (2003) indicate the need for a better knowledge of residue decomposition through a research conducted under more realistic field conditions. Likewise, in contrast to flat residues, standing residues have not been always adequately considered in tillage residue studies. Standing residues affect wind and water erosion processes differently than flat residues and, therefore, information about this residue component must be also included in studies comparing tillage systems (Steiner et al., 1994; Guérif et al., 2001).

The purpose of this study was to evaluate the effects of conservation and conventional tillage systems on the dynamics of surface barley residues during four fallow periods under both continuous cropping and cereal-fallow rotation. To this aim, values of residue cover reduction by specific tillage operations were determined and simple residue decomposition models were tested with field measurements. Likewise, a relationship between residue mass and soil cover was established for barley with prediction purposes.

2. Materials and methods

The study was conducted over a 4-yr period from Jun 1999 to Dec 2003. The experimental site was located at the dryland research farm of the Estación Experimental de Aula Dei (Consejo Superior de Investigaciones Científicas), in the Zaragoza province (41º44’N, 0º46’W, 270 m alt.), where a long-term conservation tillage experiment was initiated in 1989. Details about site and soil characteristics, crop management practices and experimental design have been previously given (López et al., 1996); therefore, only aspects relevant are repeated here. The soil is a loam (fine-loamy, mixed, thermic Xerollic Calciorthid) according to the USDA soil classification (Soil Survey Staff, 1975). The area is characterized by a semiarid climate with an average annual rainfall of 390 mm and an average annual air temperature of 14.5 ºC. Precipitation and maximum and minimum temperatures recorded at the experimental site for each year of the study are presented in Table 1.

2.1. Tillage and crop management

Three tillage treatments were compared under the traditional cereal-fallow rotation (CF) and under continuous cropping (CC) with barley (*Hordeum vulgare* L.): conventional tillage (CT), reduced tillage (RT) and no-tillage (NT). Table 2 shows the dates of cultural practices, which were the same for all tillage treatments. The CT treatment in the CC system consisted of mouldboard ploughing of fallow plots to a depth of 30-40 cm in autumn, followed by secondary tillage to a depth of 10-15 cm with a sweep cultivator just prior to sowing in November-December. In the RT treatment, primary tillage was chisel ploughing to a depth of 25-30 cm (non-inverting action), followed, as in CT, by a pass with the sweep cultivator before sowing. Under the CF rotation, primary tillage by mouldboard (CT treatment) or chisel ploughing (RT treatment) was implemented in late winter during the fallow year. In the CT and RT treatments a second tillage operation was carried out with a sweep cultivator in late spring. After this cultivation, the plots were not ploughed again until November-December when seedbed preparation with a point cultivator was carried out prior to sowing. In both cropping systems, weeds on NT plots were controlled with herbicides. A conventional planter was used in the CT and RT treatments. In NT, barley was sown directly into the crop residues from the previous harvest using a hoe drill.

Tillage treatments were arranged in an incomplete block design based on geostatistical concepts, with three replications for the RT and NT treatments and four for the CT treatment to ensure a balanced design. López and Arrúe (1995) describe in detail the experimental design and its efficiency. Accordingly, three large blocks of plots with the three tillage treatments were available on the experimental field: one block for the CC system and the other two blocks for the CF rotation. In the CF blocks, the cropping and fallowing phases were alternated as to have an experimental long-fallow period every year. The blocks were in turn arranged in a split block design with tillage as the main plot and cropping system as the subplot. The subplot size was 33.5 m x 10 m.

The present study was carried out over the fallow phases that followed the harvests of four cereal-growing seasons (1998-1999, 1999-2000, 2000-2001 and 2001-2002). Thus, during the experimental period, the CC and CF rotation involved four summer fallow periods (5-6 months) and four long-fallow periods (17-18 months), respectively (Table 2).

2.2. Crop residue measurements

Surface barley residues were sampled just after harvest and before and after any tillage and sowing operations throughout each fallow period in the CC and CF rotations (Table 2). Although no tillage operation was implemented in the NT plots, crop residues were also collected in this treatment at the same dates as those for the CT and RT treatments. Residues were collected within a 0.5×1 m^2 metal frame at four locations per plot. Standing residues (>10º from ground) were separated from residues lying flat on the soil surface. Residue samples were dried at 68 ºC for 48 hours and then weighed.

The percentage of soil surface covered with flat residues was estimated using the line-transect method (Shelton et al., 1993). This involved stretching a 5-m measuring tape diagonally at about a 45-degree angle across the crop rows and counting the number of the 10-cm marks along the tape that intercepted a piece of crop residue. The percent residue cover for the sampling area was then obtained by multiplying this count by two. Four measurements were made in each plot.

To compare the effects of tillage treatments, analysis of variance (ANOVA) for the incomplete block design was used (López and Arrúe, 1995). To evaluate the cropping system and the tillage × cropping system interaction, ANOVA according to the split block design with three replicates was performed. Duncan’s multiple range test was used to compare treatment means.

Daily precipitation and air temperature data were collected over the entire experimental period using an automatic weather station (Campbell Scientific Inc., datalogger CR10) located within the experimental field.

3. Results and discussion

3.1. Dynamics of crop residues during fallow

The variability in the seasonal rainfall pattern observed during the experimental period explains the differences in grain and residue production of barley found among the 4 years of the study. Averaged over cropping systems and tillage treatments, dry mass of residues at harvest was 1395, 729, 1742 and 1623 kg ha^{-1} in 1999, 2000, 2001 and 2002, respectively (Table 3). Although seasonal rainfall was about 200 mm in the 1998-1999 and 1999-2000 growing seasons (30% less than the long-term average for the November-June period), its distribution varied considerably. Whereas the rainfall received during the vegetative development of the crop (February-April) was near average in the 1999-2000 season (about 90 mm), in the 1998-1999 season it was 40% higher (128 mm). Likewise, similar rainfall was received in the 2000-2001 and 2001-2002 growing seasons, about 230 mm; however, whereas 50% of this rainfall fell during May and June (heading and grain filling stages of the crop) in the 2001-2002 season, this percentage was less than 30% in the 2000-2001 season. This different rainfall distribution explains that, while residue production was similar in both seasons, grain yield was, on average, twofold in 2002 than in 2001. In general, crop residues were not significantly affected by tillage or cropping system. The only noteworthy exception occurred in 2000 under CC, when there was a lower amount of residues in RT than in NT (Table 3). This was probably due to a faulty sowing in one of the RT plots, which resulted in a slightly higher residue production under CF compared with that under CC (LSD=183 kg ha^{-1}; P<0.10).

Barley residue production during the 4 years of study was within the range of 1000-2000 kg ha^{-1} that, finally, are retained on the soil surface in rainfed cereal-growing areas of semiarid

Aragon (López et al., 2003). However, residue production below 1000 kg ha^{-1}, as occurred in the present study in 2000, is not exceptional in semiarid regions where water supply is limited (Unger, 1994). Although, in these low crop residue situations, soil protection against erosion seems to be limited, the amount of crop residues produced in our study was, in general, sufficient to prevent wind erosion (López et al., 2003). Thus, in addition to flat residues, which provided soil covers normally higher than 30%, standing residues, representing between 30 and 70% of the total residue mass, were present on the soil surface in the three tillage treatments (Table 4). As is widely recognised, standing residues are more effective than flat residues in controlling wind erosion by reducing the wind speed near the soil surface and intercepting the saltating soil particles (Hagen, 1996; Nielsen and Aiken, 1998*).*

Differences among tillage treatments increased as the fallow period progressed (Table 3). After mouldboard ploughing, the residue mass retained in the CT plots under CC was 2-13% of the initial mass after harvest and only 0-2% under CF. Although the amount of residues remaining in the RT treatment was also very low after chiselling under CF (4-26% of the initial mass), differences with respect to NT became more noticeable after secondary tillage. The higher residue mass observed in the NT plots was maintained after sowing (on average, 250 kg ha^{-1} in NT, 100 kg ha^{-1} in RT and 3 kg ha^{-1} in CT). As expected, the mass of residues remaining after any cultural operation was lower under CF than under CC, as a consequence of overwinter weathering losses and a much longer time for residue decomposition in the CF system. Therefore, maintenance of sufficient residue cover becomes more difficult during the long-fallow period. In this sense, the most critical period in terms of wind erosion risk occurs under CT once primary tillage was done (López et al., 2003). Thus, under this tillage treatment, mouldboard ploughing reduced the pre-tillage cover by almost 100% (Table 5 and Fig. 1) and flattened completely the standing residues (Fig. 2). Furthermore, the risk of wind erosion at this date increases since this condition of unprotected soil surface extends normally over the most erosive months of fallowing, February-April (López et al., 2001). In contrast, under NT, and with the exception of the 2000-2001 long-fallow where residue cover was very low in all treatments (0-9%), residue covers of 20-40% remaining 9-10 months after harvest (Fig. 1) would be sufficient to reduce most of the wind erosion risk during this critical period. In the case of RT, despite of percentages of cover reduction after chiselling of 50-70% (Table 5), a combined effect of the remaining residue cover (10-20% of soil surface) and standing residues (7-19% of the total residue mass) (Figs. 1 and 2) with the roughness provided by tillage clods, would still result in a soil erodibility condition comparable to that predicted for NT (López et al., 2003). However, after secondary tillage, the residue cover decreased to values of 3-8% and standing residues disappeared from the RT plots. After 17-18 months of fallow, only the NT treatment conserved before sowing a surface residue cover of 10-15% and a percentage of standing residues ranging from 3% to even 26% of the total mass (Figs. 1 and 2).

3.2. Estimation of crop residue decomposition

As discussed above, the effectiveness of crop residues for soil protection depends on their persistence on the soil surface. Predicting the dynamics of surface residues over time is essential to evaluate residue management strategies, particularly when a long-fallow period is involved. In this sense, several models have been developed to estimate residue mass loss by decomposition under different environmental conditions. Among them, Douglas and Rickman (1992) and Steiner et al. (1994, 1999) proposed simple first-order decay equations for describing decomposition of both surface and buried crop residues in the field. Due to the simplicity in modelling and the ready availability of the information required in both cases, these models have been applied in the present study to predict loss of surface residue mass in the NT plots during long-fallow and evaluate predictions against the measured data. Briefly, the Douglas-Rickman model calculates residue decomposition from the following equation:

$$M_t = M_{t-1} \exp(-k\, f_N\, f_W\, \mathrm{CGD}) \qquad [1]$$

where M_t and M_{t-1} are residue mass at current and previous day, CGD is the cumulative degree-days, k is a general decomposition coefficient (0.0004 GD^{-1}) and f_N and f_W are factors depending on the initial N content of residues and the soil moisture availability, respectively. Decomposition is calculated in the Steiner model using the decomposition-days concept as follows:

$$M_t = M_{t-1} \exp(-k\ \mathrm{CDD}) \qquad [2]$$

where CDD is the cumulative decomposition-days based on the daily minimum of a precipitation or air temperature coefficients and k is, in this case, a crop specific decomposition coefficient (0.035 DD^{-1} for barley). Details about the determination of these coefficients can be found in Steiner et al. (1994, 1999) and Schomberg et al. (1996).

Fig. 3 shows predicted and measured mass loss of barley residues under NT during the four long-fallow periods of the study. After the 17-18 months of fallow, 80-90% of the initial residue mass was lost, corresponding 60-75% of this loss to the first 9-10 months after harvest. In spite of the limited number of experimental data to test the models, in general, both models satisfactorily simulated the decline of residue mass over time. It is true that there was some overprediction in the 1999-2000 fallow period and a general underprediction in the 2002-2003 fallow with the Douglas-Rickman model. A more adequate evaluation of the models was made by using the normalized objective function, NOF (Costa et al., 1994; Ma et al., 1999). The NOF is calculated as the root mean square error divided by the mean of the measured values and should be interpreted as a relative value to compare different model performances; if all predicted and measured values are the same, then NOF would yield a zero value. As shown in Table 6, the NOF value for each fallow period was similar to its coefficient of variation (CV), indicating that the deviation of the model simulation from the experimental data was similar to the experimental error. However, the Steiner model, with overall lower NOF values, performed better than the Douglas-Rickman model. The main differences between model predictions were found during the first two-three months of the 2000-2001 and 2001-2002 fallow periods, when the Douglas-Rickman model predicted faster residue decomposition than did the Steiner model, and after those first months in the 2002-2003 fallow, when the opposite occurred (Fig. 3). Although, unfortunately, the lack of experimental data during the first months impeded an accurate evaluation, the Steiner model seemed to reflect better the influence of climatic conditions on residue decomposition. Thus, the flatness of the curve predicted by this model for the period from early July to mid September in the 2000-2001 and 2001-2002 fallows indicates that climatic conditions limited initial residue decomposition; furthermore, soil moisture was the limiting factor since only 11 and 6 mm of precipitation was received during this warm period in the 2000-2001 and 2001-2002 fallows, respectively. In contrast, in the 2002-2003 fallow, the higher decomposition rate estimated with the Steiner model reflected more accurately the combined effect of frequent precipitation from mid September to the end of October (total of 110 mm) and, still, no limiting temperatures for microbial activity during these months (average of 19ºC and 15ºC for September and October, respectively). The different responses of both models were probably related with the different way to consider the effect of soil moisture on residue decomposition. Thus, whereas in the Steiner model the soil moisture factor is estimated in the CDD calculation (Eq. [2]) from daily precipitation data, in the Douglas-Rickman model is just a constant value, f_W (Eq. [1]), that depends only on crop residue placement and field management (i.e. f_W=0.3 for surface residues in fallow fields). All the above indicates that, although predicted results from both models reflected the general trend in residue mass change during fallow, the Steiner model may be more appropriate for describing surface residue changes under the study area conditions with low and highly variable precipitation. The greater sensitivity of this model to climatic conditions is also explained by the use of the decomposition-days concept, relating temperature and moisture conditions to those for optimum rates of decomposition. Ruffo and Bollero (2003) came to a similar conclusion in modelling cover crop residue decomposition under rainfed conditions using CGD and CDD. In spite of all above, more experimental data throughout the entire fallow period would be required for a more accurate validation of models in our study area.

3.3. Residue cover reduction by tillage

Tillage has a considerable effect on the placement and distribution of crop residues. Consequently, the evaluation of individual tillage operations must be considered in planning effective fallow management systems for erosion control or other conservation purposes. In this sense, the values of residue cover reduction by tillage found in our study (Table 5) are, in general, in agreement with those published originally by the USDA Soil Conservation Service and the Equipment Manufacturers Institute (SCS-EMI, 1992) and later adapted by Shelton et al. (1995). Thus, a single pass of a mouldboard plough had the greatest influence on residue incorporation with reduction percentages of 90-100%, a range similar to that provided by SCS-EMI (1992). With chiselling, the burial percentages (40-70%) were equal to those given by Shelton et al. (1995) for chisel ploughs with similar characteristics (straight spike points). The reduction percentages for the cultivators used for secondary tillage (30-50%) and seedbed preparation (60-70%) were slightly higher than those estimated by the SCS-EMI for similar implements (25-40% and 50-65% for a field cultivator with sweeps and duckfoot points, respectively). Likewise, the conventional planter used in our study buried a slightly greater proportion of residues (20-30%) than that estimated by the SCS-EMI (10-20%). For the hoe opener drill, the residue cover losses were similar to those previously published (40-60%). When comparing our measurements with the published values, we have taken into account that tillage operations were performed over a month later and, therefore, a higher reduction in the residue cover should be expected, with percentages closer to the upper values of the SCS-EMI ranges. Similarly, the low pre-tillage residue cover and the fragile nature of our barley residues have also been taken into account as comparison criteria.

3.4. Soil cover prediction from residue mass

Whereas most crop residue studies related to erosion control or the effect of tillage operations on residue retention express residue data, primarily, as percentage of soil cover, studies dealing with residue decomposition usually calculate residue losses in terms of mass. Due to the time and labour involved in obtaining residue mass data and the difficulty attributed to residue cover determination methods (Li and Chaplin, 1998; Daughtry, 2001), there is an interest in establishing relationships between residue mass and soil cover for prediction purposes. Thus, the percentage of residue cover (RC) can be estimated from the residue mass per unit area (RM) following the exponential equation developed by Gregory (1982):

$$RC = 1\text{-}\exp(-A_m\, RM) \qquad [3]$$

where A_m is a mass-to-cover coefficient. Relationships of this type have been described for many crops and, frequently, soil cover has been estimated from total residue mass. However, Steiner et al. (2000) suggested that the use of flat residue mass is most adequate than total mass to predict soil cover when extended periods of time are involved. These authors demonstrated that, as residues decompose and shift from standing to flat, the A_m value increases when total residue mass is considered. In contrast, the relationship between flat residue mass and cover is relatively stable with time and an unique average value of A_m could be used to predict soil cover (Steiner et al., 2000). Following the findings of Steiner et al. (2000), equation [3] was used to generate a curve relating percentage of residue cover to flat residue mass per area from the experimental data obtained in our study (Fig. 4). The data were pooled across dates, tillage treatments and cropping systems to obtain a wide range of values. Data from the harvest of the 2002-2003 growing season were also used to have values of residue cover close to 100% (for flat residue mass of 2000-3500 kg ha^{-1}). In spite of the scattering of the experimental data, the trend of the data was well described by the regression curve (r=0.922; P<0.0001). The value of the A_m coefficient obtained from the regression was 0.00208 ha kg^{-1}, a figure very close to the average of 0.00172 ha kg^{-1} reported by Steiner et al. (2000) for barley (Fig. 4). These results indicate that, for the study area conditions, barley residue cover could be estimated from flat residue mass through the fallow period by using 0.00208 ha kg^{-1} as a single A_m value.

4. Conclusions

Results on the evolution of surface barley residues during four fallow periods indicate that the lack of residue-disturbing operations in NT makes this practice the best strategy for fallow management in semiarid Aragon. With this tillage system, soil surface was protected by sufficient amount of standing and flat residues in the most critical period of wind erosion during long-fallow. In both CT and RT, primary tillage operations had the major influence on residue incorporation. Thus, mouldboard ploughing (CT) buried almost total surface residues and chiselling (RT) reduced the pretillage-cover to less than half and flattened most of the standing residues.

The decline of surface residue mass under NT during long-fallow was adequately simulated by the Douglas-Rickman and the Steiner decomposition models. However, more accurate estimations were obtained with the Steiner model, indicating that the CDD function may be a better estimator of weather effects than CGD for the study region conditions. Thus, based on field observations, the Steiner model appears a simple and adequate tool for predicting persistence of surface barley residues in fallow lands of semiarid Aragon. Likewise, the mass-to-cover relationship established in this study for barley residues could be used to estimate soil cover from flat residue mass throughout the fallow period by using a single A_m coefficient (0.00208 ha kg^{-1}).

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Figure legends

Figure 1. Barley residue cover during the 2002-2003 fallow period of the cereal-fallow rotation as affected by tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage). Bars indicate LSD (P<0.05) for comparisons among tillage treatments at the same date, where significant differences were found.

Figure 2. Evolution of standing barley residue mass during the 2001-2002 fallow period of the cereal-fallow rotation under different tillage treatments (CT, conventional tillage; RT, reduced tillage; NT, no-tillage). For the same date, different letters indicate significant differences at P<0.05.

Figure 3. Measured and estimated mass loss of barley residues under no-tillage during four fallow periods of the cereal-fallow rotation. The solid lines represent estimations from the models of Douglas and Rickman (1992) and Steiner et al. (1994, 1999).

Figure 4. Relationship between soil cover and flat residue mass per unit area for barley crop. A_m is the mass-to-cover coefficient. See text for details.

Table 1. Total monthly precipitation (*P*) and mean monthly maximum and minimum temperatures (*T*) recorded at the experimental site during the 1999-2003 period.

	1999			2000			2001			2002			2003		
	P	*T* (ºC)		*P*	*T* (ºC)		*P*	*T* (ºC)		*P*	*T* (ºC)		*P*	*T* (ºC)	
	(mm)	Max.	Min.	(mm)	Max.	Min.	(mm)	Max.	Min.	(mm)	Max.	Min.	(mm)	Max.	Min.
Jan.	11.0	10.9	-0.1	14.3	9.0	-1.6	44.4	11.4	2.9	22.2	11.1	2.3	31.5	11.0	1.1
Feb.	20.5	13.1	1.9	1.0	17.1	2.4	3.6	13.8	1.5	6.1	15.2	2.9	41.0	10.9	1.2
Mar.	62.0	17.2	3.9	25.1	18.2	3.8	21.4	19.5	6.8	48.1	18.2	5.5	37.0	18.2	4.0
Apr.	45.6	20.3	7.3	62.0	18.4	6.3	5.2	20.4	6.1	27.1	20.2	6.0	31.9	20.4	6.6
May	34.8	26.1	12.0	39.8	25.7	11.4	53.5	25.2	10.1	72.5	22.9	9.4	69.1	25.2	9.9
June	17.3	29.0	13.2	47.5	30.0	14.2	9.1	31.9	13.9	40.4	30.4	14.5	27.1	34.2	17.6
July	26.9	33.0	17.0	3.6	30.9	15.9	3.4	32.0	15.3	17.3	31.0	15.9	0.6	34.1	17.8
Aug.	8.9	32.0	17.1	7.3	32.9	16.0	2.2	33.3	17.6	8.5	29.5	16.1	10.3	35.4	18.3
Sep.	46.3	26.8	14.7	9.1	28.8	12.7	59.4	25.7	11.5	59.6	26.4	12.6	65.9	26.0	13.8
Oct.	33.3	21.0	9.3	121.6	20.5	9.5	24.6	23.7	11.7	53.9	21.4	9.2	61.4	19.4	9.4
Nov.	15.2	12.1	2.8	65.5	14.2	4.5	10.3	13.8	2.7	14.5	16.5	6.0	47.9	15.4	4.8
Dec.	6.9	11.1	0.5	36.4	12.9	3.6	2.6	8.5	-3.2	33.5	12.7	4.6	18.6	10.8	2.6

Table 2. Schedule of agronomic practices and crop residue sampling during fallow in the continuous cropping system (CC) and the cereal-fallow rotation (CF).

Cropping system	Fallow period (Harvest-Sowing)	Primary tillage	Secondary tillage	Seedbed preparation	Sowing	Crop residue sampling
		days after harvest				
CC	21 Jun 1999-4 Nov 1999	94	135	-	136	3, 92, 94, 129, 135, 141
	20 Jun 2000-13 Dec 2000	155	175	-	176	7, 153, 167, 175, 176
	29 Jun 2001-23 Nov 2001	108	145	-	147	3, 101, 108, 144, 145, 147
	27 Jun 2002-26 Nov 2002	140	151	-	152	6, 139, 141, 151, 154
CF	21 Jun 1999-13 Dec 2000	309	343	540	541	3, 283, 316, 340, 344, 532, 540, 541
	20 Jun 2000-23 Nov 2001	294	351	519	521	7, 293, 295, 350, 352, 518, 519, 521
	29 Jun 2001-26 Nov 2002	257	347	514	515	3, 251, 257, 339, 347, 511, 514, 517
	27 Jun 2002-2 Dec 2003	265	334	525	525	6, 263, 266, 333, 335, 518, 525, 526

Table 3. Dry mass of barley residues remaining after specific cultural practices applied during fallow under different tillage treatments (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) and cropping systems (CC, continuous cropping; CF, cereal-fallow rotation).

Year	Cropping system	Tillage treatment	Grain yield (kg ha^{-1})	Residue mass (kg ha^{-1}) retained after				
				Harvest	Primary tillage	Secondary tillage	Seedbed preparation	Sowing
1999	CC	CT	1489	1276	162	16	-	24
		RT	1153	1424	974	193	-	154
		NT	1052	1302	1424	992	-	427
		LSD (0.05)[a]	NS	NS	531	282	-	105
	CF	CT	2754	1855	0	0	0	0
		RT	1806	1388	355	208	26	22
		NT	1396	1126	581	498	219	118
		LSD (0.05)	981	NS	177	69	47	42
2000	CC	CT	877	618	22	0	-	0
		RT	467	341	125	40	-	36
		NT	634	850	648	648	-	229
		LSD (0.05)	207	327	204	194	-	42
	CF	CT	1491	850	4	0	0	0
		RT	1727	879	36	26	4	0
		NT	923	837	269	178	85	49
		LSD (0.05)	672	NS	85	64	34	18
2001	CC	CT	1437	1605	32	0	-	0
		RT	1211	1515	1141	284	-	381
		NT	902	1845	1220	741	-	613
		LSD (0.05)[a]	NS	253	464	154	-	276
	CF	CT	1620	1928	26	5	0	0
		RT	1374	1715	371	136	34	24
		NT	1139	1842	856	736	342	126
		LSD (0.05)	NS	NS	229	82	145	69
2002	CC	CT	2747	1728	30	0	-	0
		RT	1818	1368	348	179	-	178
		NT	1386	1515	851	851	-	366
		LSD (0.05)	NS	NS	450	332	-	101
	CF	CT	3106	2103	32	0	0	0
		RT	3082	1479	365	93	15	7
		NT	3578	1545	559	280	159	75
		LSD (0.05)	NS	NS	174	41	32	25

[a] Least significant difference, *P*<0.05. NS, not significant.

Table 4. Soil cover by flat residues and dry mass of standing residues of barley after harvest under different tillage treatments (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) and cropping systems (CC, continuous cropping; CF, cereal-fallow rotation).

Year	Cropping system	Tillage treatment	Residue cover (%)	Standing residue mass (kg ha^{-1})
1999	CC	CT	65.7	608
		RT	69.8	600
		NT	69.3	548
		LSD (0.05)[a]	NS	NS
	CF	CT	78.3	578
		RT	76.7	520
		NT	48.7	571
		LSD (0.05)	10.9	NS
2000	CC	CT	27.5	276
		RT	14.8	170
		NT	38.5	353
		LSD (0.05)	7.8	NS
	CF	CT	39.5	363
		RT	36.3	352
		NT	33.7	420
		LSD (0.05)	NS	NS
2001	CC	CT	74.8	1131
		RT	79.7	1030
		NT	79.5	1230
		LSD (0.05)[a]	NS	NS
	CF	CT	79.5	1107
		RT	88.2	1003
		NT	78.2	1159
		LSD (0.05)	NS	NS
2002	CC	CT	58.3	536
		RT	62.8	419
		NT	66.8	549
		LSD (0.05)	NS	NS
	CF	CT	67.2	482
		RT	71.7	466
		NT	72.8	473
		LSD (0.05)	NS	NS

[a] Least significant difference, $P<0.05$. NS, not significant.

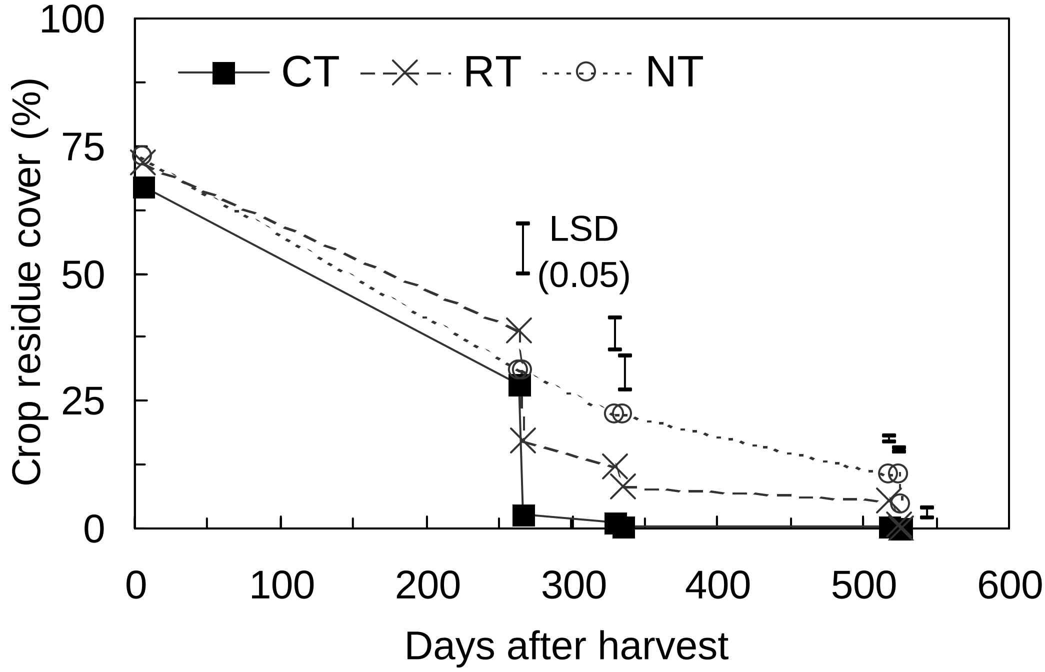
Table 5. Influence of field operations during fallow on barley residue cover reduction under different tillage treatments (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) and cropping systems (CC, continuous cropping; CF, cereal-fallow rotation)

Cropping system	Tillage treatment	Percentage of cover reduction after: Primary tillage	Secondary tillage	Seedbed preparation	Sowing
CC	CT	89-94	100[a]	-	-
	RT	39-67	27-32	-	18-33
	NT	-	-	-	33-44
CF	CT	90-100	100[a]	-	-
	RT	51-72	34-50	61-73	90-100[a]
	NT	-	-	-	52-60

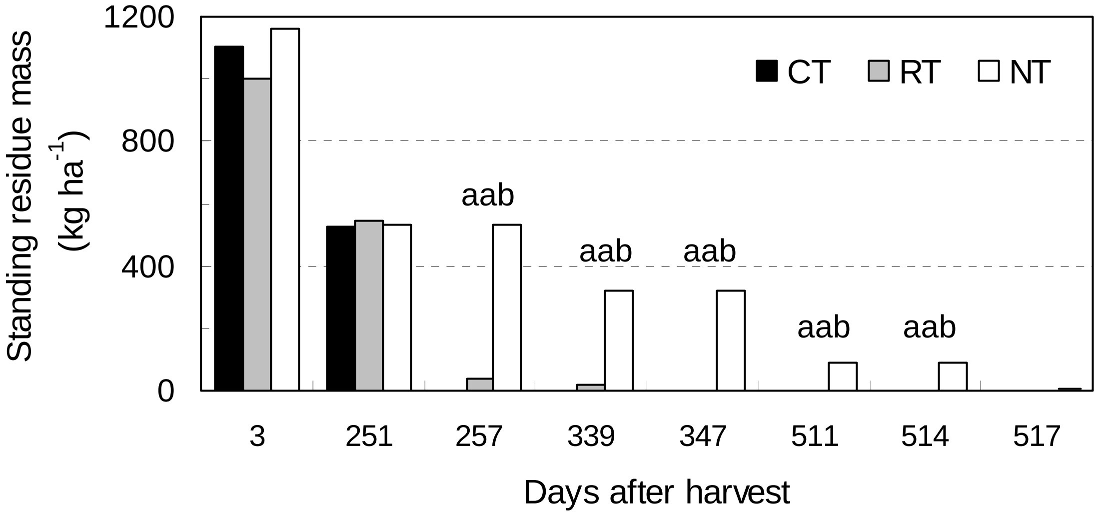
[a] Initial residue cover is null or negligible (<2%).

Table 6. Comparison of model predictions based on the normalized objective function (NOF) and the coefficient of variation (CV) of the experimental data.

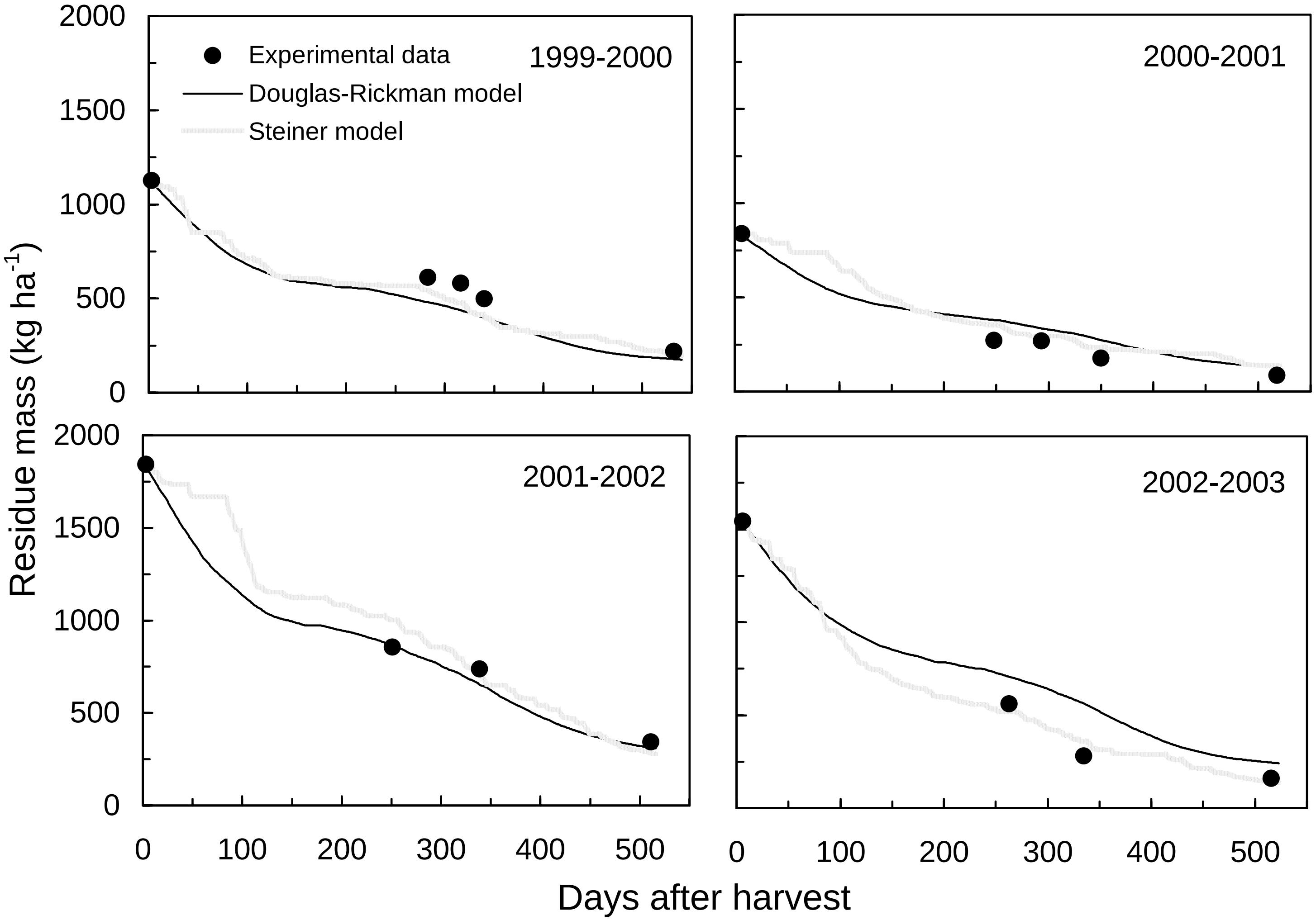
Fallow cycle	NOF		CV
	Douglas-Rickman model	Steiner model	
1999-2000	0.36	0.34	0.35
2000-2001	0.53	0.50	0.50
2001-2002	0.29	0.30	0.34
2002-2003	0.39	0.30	0.31
Average	0.39	0.36	0.38



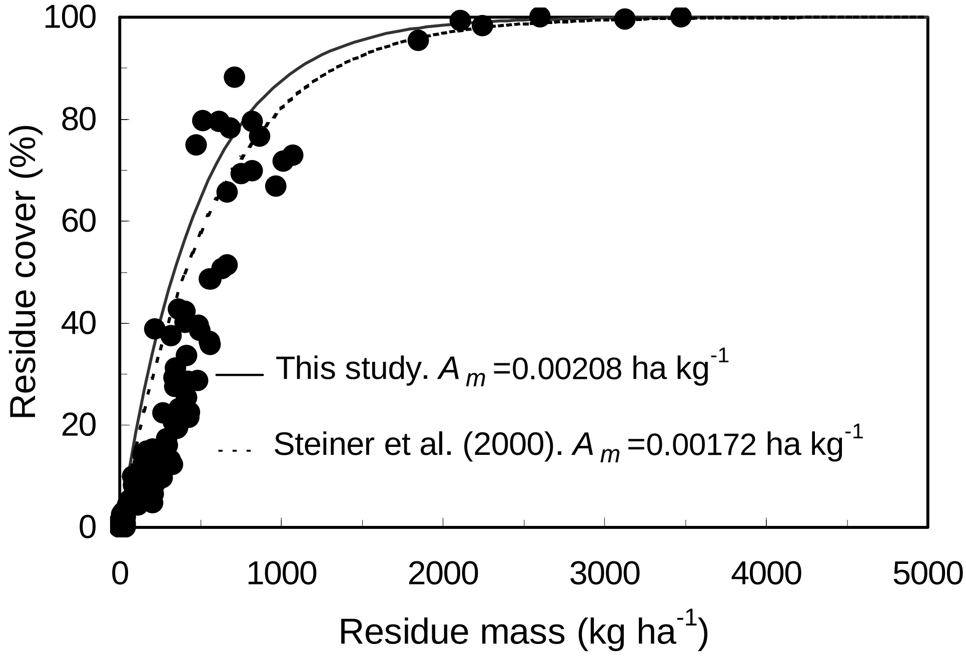
100
75
50
25
0
Crop residue cover (%)
CT
RT
NT
LSD
(0.05)
0
100
200
300
400
500
600
Days after harvest



Standing residue mass (kg ha-1)
1200
800
400
0
CT
RT
NT
aab
aab
aab
aab
aab
3
251
257
339
347
511
514
517
Days after harvest



Experimental data
Douglas-Rickman model
Steiner model
1999-2000
2000-2001
2001-2002
2002-2003
Residue mass (kg ha^{-1})
Days after harvest
0
500
1000
1500
2000
0
100
200
300
400
500



100
80
60
40
20
0
Residue cover (%)
This study. A_m =0.00208 ha kg^{-1}
Steiner et al. (2000). A_m =0.00172 ha kg^{-1}
0
1000
2000
3000
4000
5000
Residue mass (kg ha^{-1})